CIBTech Journal of Zoology ISSN: 2319–3883
Online, International Journal, Available at http://www.cibtech.org/cjz.htm
2022 Vol.11, pp.104-136/Pankaj and Prama
***Review Article** (Open Access)*

MICROPLASTIC OCCURRENCE AND BEHAVIOR IN FRESHWATER ECOSYSTEMS

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ABSTRACT

Availability of fresh potable water in the world is a major challenge. Microplastic pass in the aquatic environment mainly from the terrestrial sources that travel with the rivers and through intense human activities around the water bodies. Lot of work focuses upon the presence and behavior of microplastic in oceans and seas but comparatively less emphasis is given to study of microplastic behavior in the freshwater bodies. Occurrence of microplastic in the freshwater systems is of great concern since the freshwater systems sustain most of the human settlements. The current study aims to focus on microplastic contamination of the inland fresh water bodies, like lakes and rivers and their sediments that are surrounded by dense population and can be a potential source of microplastic in the food chain.

Keywords: *Microplastics, Bioaccumulation, Freshwater, Lakes, Rivers, Sediments, Polypropylene, Polyethylene*

INTRODUCTION

Plastics have become necessary and unavoidable parts of our life. They find entry in almost all commodities that we use on daily basis. The word plastic comes from a Latin word “plasticus” derived from “plastikos” a Greek term which was used in the 17th century for something that could be molded or was fit for molding (Joel 1995). Due to its non-fragile, resistant, non- biodegradable, non-corrosive or non-rusting properties, it has replaced paper, glass, wood and even metals widely. Materials made from plastics can be molded into variety of shapes, sizes and forms, and are mostly lightweight, hygienic, resistant (UNEP 2018), strong, durable, can be used at a diverse range of temperatures, and as electrical insulators (Mazhandu *et al*., 2020) so they have wide range of applications.

Plastics are organic polymers formed by organic carbon-based monomer molecules (units) that are joined to form macromolecule chains which form the basic structure of plastics (Klein 2011; Verla *et al*., 2019). The macromolecule chains are brought together by characteristic polymerization reactions viz. polyaddition (step or chain reactions) and polycondensation reactions (Gowariker *et al*., 2005; Klein 2011). The components of the monomer units are: carbon, hydrogen, oxygen, nitrogen, sulfur, fluorine or chlorine; out of which carbon and hydrogen form the major components while the other molecules may or may not be present. Different types of plastics contain different kind of element with variations in their position and proportion in the monomer molecule (Edmondson and Gilbert 2017).

Plastics are divided into thermoplastic, thermoset and elastomers on the basis of changes in physical properties with temperature, while thermoplastics are hard at normal temperature but can melt on heating and are affected by application of mechanical and radiation energy whereas thermosets are hard at normal temperature but cannot melt on heating, lastly elastomers have elasticity but cannot be melted (Klein 2011). Polypropylene (PP), polyethylene (PE) and polyvinyl chloride (PVC) are examples of thermoplastic; examples of thermosets are polyesters (PEST), epoxy resins and phenolic resins while examples of elastomers include polyurethanes (PU), butadiene elastomers (BE), styrene-butadiene-elastomers (SBE) (Klein 2011). On the basis of their utilization plastics are grouped into general and engineering plastics (Yuan 2009). General plastics comprise of PE, PP, PVC, PU, PS (polystyrene) and phenolic resin (Chen *et al*., 2021) while engineering plastics are high performance plastics that include co-polyester elastomers (COPE), polyether block amides (PEBA) (Klein 2011). Based on their origin, they may be grouped into natural and synthetic plastics. Generally, polymers produced from renewable sources are termed as natural polymers while polymers that are produced from non-renewable petroleum resources are termed as synthetic polymers (Vroman and Tighzert 2009).

Items made from plastic are widely used in packaging, medical, transportation, pharmaceutical sectors (Shah *et al*., 2008; Mazhandu *et al*., 2020). PP and PE are usually found in the normal use plastic products like disposable beverage bottles, disposable plastic containers for storing food items, table ware (straws, cups, cutlery), grocery bags, packaging material used for pharmaceuticals, detergents, cosmetics, chemical products etc. (Shah *et al*., 2008; Zhang *et al*., 2012; Kankanige and Babel 2020; Chen *et al*., 2021). Since these plastics are used only once, they are termed as single-use plastics (SUPs) that are ultimately disposed in landfills, incinerated and if not managed properly they find way in soil, oceans, lakes and rivers causing pollution (Boucher *et al*., 2019; Chen *et al*., 2021). About 39.6% of the plastics produced worldwide are used in packaging (Plastics Europe, 2020), and these have comparatively shorter lifespan but wide application, they are cheap, disposable and thrown off in the environment (Geyer *et al*., 2017; Zhang *et al*., 2018).

Plastic production depends upon oil, a fossil fuel, which is a scarce, non-renewable resource. According to an estimate roughly 4% of the world's oil is utilized as raw material in making plastic and about 3-4% is required to supply energy in its production (Hopewell *et al*., 2009; Tuladhar and Yin, 2019). According to World Economic Forum (2016), by the year 2050, around 20% of petroleum would be used in manufacturing and processing of plastics on a global level and may contribute to 15% of the yearly carbon emissions budget. Production of plastic on global level, raised from 359 million tons in 2018 to 368 million tons in 2019, major production rate being in Asia i.e., 51% (PlasticsEurope 2020). According to a report about 400 Mt of CO_2 is released every year as a result of plastic production and plastic waste incineration (Plastics Europe, 2018).

Management of large amount of plastic waste is serious problem associated with plastic consumption. About 6300 Mt tons of plastic waste was generated on a global level in 2015; out of which only 9% was recycled, 12% got incinerated and 79% was discarded in landfills or thrown off in various environmental components (Geyer *et al*., 2017; Robin *et al*., 2019). Plastic products release quiet a large number of chemical additives and toxic chemicals in the oceans and sea; major contributor being plasticized PVC (Suhrhoff and Scholz-Böttcher, 2016; Crawford and Quinn 2017). Disposal of plastic waste also has associated problems for example burning of waste containing polyvinylchloride (PVC) plastic products leads to generation of persistent organic pollutants (POPs) as furans and dioxins (Jayasekara *et al*., 2005; Shah *et al*., 2008). When disposed in landfills and dumping grounds plastics persist for years due to their non degradable nature. Unmanaged plastic waste may litter around and lead to clogging of sewers, accumulation of waste water, diseases due to breeding of mosquitoes and disease-causing pests, death of domesticated animals like cows, buffaloes due to ingestion, find entry in the lakes, rivers and reservoirs, release of toxic materials in soil or water reservoirs, death of aquatic organisms due to choking or entanglement, ultimately affecting the food chains and ecosystems (UNEP 2018; Ncube *et al*., 2021). Plastic pollution also imposes economic burden on the nations as it creates hinderance in smooth functioning of industries like marine fisheries, aquaculture, pisciculture, tourism and other sectors due to plastic litter pollution (Brouwer *et al*., 2017; Robin *et al*., 2019; Beaumont *et al*., 2019). When plastic is exposed to environmental stresses like temperature fluctuations, UV radiations, mechanical stress (like oceanic wave action and ocean circulation or wear and tear in terrestrial ecosystem), or oxygen variation, it breaks down into small pieces leading to generation of nano and microplastic (MP) thus affecting the environment especially aquatic ecosystems (Andrady 2011; Brennecke *et al*., 2016; Robin *et al*., 2019; Chouchene *et al*., 2021). Studies indicate that microplastic is widely distributed in different components of the environment and have been reported from beaches, freshwater bodies (Turner and Holmes 2015; Anderson *et al*., 2017), sediments (Bergmann *et al*., 2017), coastal soil (Zhao *et al*., 2018), estuarine areas

(Gray *et al*., 2018), oceans, atmospheric dust (Prata 2018), living organisms (Smith *et al*., 2018) even in far-flung areas like sea ice of the Arctic and the Antarctic (Waller *et al*., 2017).

Microplastic that enter the environment reach food chain and ultimately affects the human beings. MPs enter humans through several routes like consumption of sugar, honey (Liebezeit and Liebezeit 2013), contaminated seafood (Smith *et al*., 2018), polluted sea-salt (Yang *et al*., 2015; Kosuth *et al*., 2018), beer (Kosuth *et al*., 2018), potable water (Kankanige *et al*., 2020) etc. Lot of work focused upon the presence and behavior of MP in oceans and seas but comparatively less emphasis is given to study of MP in the freshwater bodies.

The current study aims to focus on MP contamination of the inland fresh water bodies, like lakes and rivers and their sediments that are surrounded by dense population and can be a potential source of MP in the food chain. Availability of fresh potable water in the world is a major challenge. Lakes and rivers sustain livelihood of people through fisheries and tourism. The fresh water resources have been depleted and polluted in several parts of the world due to rapid urbanization, population growth, industrialization, changing lifestyles and several other anthropogenic sources.

A detailed and comprehensive search was carried out on all available database like Google scholar, ISIWeb of Science, PubMed, Science Direct. The keywords searched were: microplastics, freshwater, lakes, rivers, sediments, microplastic types, health impacts, etc. Research articles focusing on the microplastic pollution in lakes, rivers and streams were taken into consideration and following information was retrieved: (i) Classification of MP (ii) Characteristics of MP in freshwater bodies (iii) Source of MP in fresh water bodies (iv) Behavior of MP in fresh water bodies (v) Abundance and characterization of MP in lakes, rivers and their sediments (vi) Freshwater organisms affected by MP.

1. MICROPLASTICS IN FRESHWATER BODIES

1.1. *Classification*

Plastics are classified on the basis of their size as microplastic and macroplastics (Boucher *et al*., 2019). Microplastics (MP) are defined as minute plastic fragments that are less than 5mm in their largest dimension, covering a wide range of shapes and sizes (that may include 1D-fibers, 2D-fragments and 3D-spheres) and are divided into primary and secondary microplastics (Duis and Coors 2016; Dris *et al*., 2016; Chouchene *et al*., 2021). Primary MPs are originally manufactured in small microscopic size i.e., less than 5mm intended to perform specific direct functions as microbeads in cosmetics (Duis and Coor 2016), as air-blasting media (Napper and Thompson 2020), in cleaning products (Cole *et al*., 2011), may be produced through plastic extrusion or grinding (Chouchene *et al*., 2021), or as feed stock for making various products (Turner and Holmes 2015). When unmanaged plastic waste gets broken down under extreme conditions like temperature, ultra violet radiations, mechanical stresses like wave abrasion, microbial disintegration or other weathering processes it leads to formation of secondary plastics (Cole *et al*., 2011; Boucher *et al*., 2019; Zheng *et al*., 2020; Issac and Kandasubramanian 2021). Macroplastics are of size greater than 5 mm in diameter and these undergo fragmentation and lead to formation of secondary microplastics (Boucher *et al*., 2019; Zhao *et al*., 2018; Couchene *et al*., 2020).

It has been observed that while classifying and defining MPs on the basis of their size range, upper limit clearly finds mention but not the lower limit as different methods of sampling have been employed in different studies (Andrady 2011; Duis and Coors 2016; Pivokonsky *et al*., 2018). Thus, some scientists have classified particles smaller than 1µm as nanoplastics (Cole *et al*., 2011). Hartmann *et al*., (2019) classified plastics keeping in mind the SI system as- nanoplastics: 1 to less than 1000 nm, microplastics: 1 to less than 1000 µm, mesoplastics: 1 to < 1000 mm and macroplastic: 1cm and larger particles. They proposed that in case of multiple dimensions, the largest dimension should be considered as this will govern its ingestion by the aquatic organisms.

Some authors propose to classify plastic waste as mesoplastic ranging from 1 mm to 2.5 cm, microplastics ranging from 1 to 1000 µm and nanoplastics which are less than 1 µm in size (Freeman *et al*., 2020). Many studies suggest that plastic particles less than 1mm be considered as MP especially in marine environment, since this size range is most common in marine environments, also considering their micrometer size range (Browne *et al*., 2011; Dekiff *et al*., 2014; Kane and Clare 2019). On a broad scale MP have been defined as ranging from <5 mm to 250 mm in diameter (Arthur *et al*., 2009; Andrady 2011; Pivokonsky *et al*., 2018; Kane and Clare 2019).

1.2 *Sources*

Microplastics may be abundantly found in dense urban (mainly secondary plastics) or industrialized areas (mostly primary plastic) but waste management problems exist across the globe so they find entry in terrestrial, freshwater as well as marine environments due to their pervasive and persistent nature (Andrady 2011; Boucher *et al*., 2019; Veerasingam 2020). Some other sources include abrasion and scraping of paints (Lassen *et al*., 2015), rejected or lost fishing equipment and nets (Andrady 2011) and textile (Rist and Hartmann 2018). MP pass in the aquatic environment mainly from the terrestrial sources that travel with the rivers and through intense human activities around the water bodies like tourism, fishing, industrialization, sewage discharge, plastic manufacturing plants, plastic decomposition etc. (da Costa *et al*., 2016; Pivokonsky *et al*., 2018). Municipal discharge, urban runoff, sewage discharge are prominent sources of MP in rivers and lakes (Sighicelli *et al*., 2018). There is addition of MP in road dust in the form of TRWP i.e., tyre and road wear particles, generated by abrasion of vehicle tyre which enters the water bodies with the rainwater runoff through sewer (Siegfried *et al*., 2017; Zhang *et al*., 2018). TRWP may also enter the water bodies through air dust or soil and it is estimated that 13% to 15% of MP in the river ecosystem is contributed as TRWP (Verschoor *et al*., 2016). Windblown MP from the dumpsites, landfills, river and lake catchment and atmospheric fallout may add considerable amount of MP in water bodies situated close by or even that are situated far off (Zhang *et al*., 2018). Plastic finds use in plastic mulching and also in microcapsule fertilizers in agriculture sector where they are used to enhance the crop yield but the microplastic gets incorporated in soil negatively affecting the soil microenvironment (Katsumi *et al*., 2020). The textile sector is also a large consumer of plastic in form of synthetic fibers. Studies confirm that synthetic textile fibers produce microplastic fibers during their use or washing (Browne *et al*., 2011; Zhang *et al*., 2018).

Angling baits are also potential source of MP for fish in areas where angling is a common recreational activity especially in European countries where about 20% of the population is engaged in this sport and it is reported that the amount of MP varies with the type of baits and manufacturing process involved and plant-based baits were found to contain more MP than animal-based baits (de Carvalho *et al*., 2021).

Studies have proved that most prominent source of MP pollution in rivers is human settlement. It has been proved that more than 80% MP in rivers of urban area enters from improperly treated sewage water (Cheung and Fok 2017). Untreated or poorly treated waste water coming from the municipal areas is a major source of MP. Slums and rural areas with poor sanitary conditions are potential contributors of MP in rivers (Alam *et al*., 2019). The waste water generated from rural areas acts as a non-point source adding MP in lakes and rivers since waste water treatment facilities are not present here (Su *et al*., 2016). Even the waste water treatment plants in the urban areas fail to trap and retain very small sized plastic pollutants, thus releasing a considerable amount of MP with the treated water in receiving water bodies (Murphy *et al*., 2016; Zhang *et al*., 2018; Li *et al*., 2018b; Freeman *et al*., 2020). The sewage sludge obtained after the waste water treatment also contains large amount of MP and if disposed on land MP enters nearby water bodies with the storm water runoff (Mahon *et al*., 2017; Zhang *et al*., 2018). Medical facilities also contribute MP, as they are used in dental and pharmaceutical carriers (Issac and Kandasubramanian 2021). Su *et al*., (2016) reported that 22 main influent rivers that run across developed areas entering the Taihu Lake of China are main source of MP in the lake, so rivers that flow in the lakes act as transporters and carriers of MP.

The presence of MP in the far-flung areas of Arctic and Antarctic region, may be due to transportation along with the ocean currents and wind. Considerable quantity of MP found in Arctic ice may be attribute to atmospheric deposition (Bergmann *et al*., 2017). In more recent studies MPs have been detected in the deep-sea sediments of Mediterranean Sea, Bohai sea, Yellow sea, Northwest Pacific ocean, Atlantic ocean and Arctic ocean (Van Cauwenberghe *et al*., 2013; Fischer *et al*., 2015; Bergmann *et al*., 2017; Zhao *et al*., 2018).

MP have been detected even in the ground water but their concentration has been found to be negligible, still it is a matter of concern since in many parts of the world ground water is a significant and only source of drinking water (Bouwman *et al*., 2018; Mintenig *et al*., 2019).

1.3 *Characteristics of MP*

2.3.1 *Shape*: MPs occur in various shapes ranging from fragments, fibers, granules, foams, tubes (Chouchene *et al*., 2021), pellets, sponges, flakes, films (Zhou *et al*., 2018), foils, spheres (Anderson *et al*., 2017; Pivokonsky *et al*., 2018). The shape of the microplastic particles widely vary and depend upon its origin and source. There is no consensus in sorting of MP on the basis of their shapes. A comprehensive and advanced way of classifying MP is spheres, spheroids (irregular spheres), cylindrical pellets, fragments (irregular shaped particles), films and fibers (Hartmann *et al*., 2019). According to Qiao *et al*., (2019), the shape of MP particle is useful in evaluating its source, movement and the toxicity potential in the aquatic ecosystems. Large number of studies confirmed that fibers are the most abundant MP type found, especially on sites which are close to residential areas or that receive domestic waste water (Cole *et al*., 2011; Anderson *et al*., 2017; Alfonso *et al*., 2020; Bertoldi *et al*., 2021). Major source of fibers in domestic waste water was found to be washing and wearing of synthetic textiles (Alfonso *et al*., 2020). Fishing industry is also a potential contributor of MP in lakes since wear and tear of the fishing nets, ropes and canvas leads to generation of fibrous MP. Dris *et al*., (2015), in their study have reported that about 90% of MP entering in lakes of Paris was due to Atmospheric fallout, where fibers were dominant, ranging between 30-300 particles/m^2 in abundance. A point to be noted here is that the abundance of fibrous MP may also be due to the ease with which they can be identified (Alfonso *et al*., 2020).

Another major type is secondary MP formed by the breakdown of big plastic particles into small and ultimately to micro fragments (Bertoldi *et al*., 2021; Egessa *et al*., 2020). Since, plastic debris are resistant and persist in freshwater ecosystem so they are subjected to UV degradation and other stresses to form fragmented MP. Many studies have reported abundance of fragments in lakes (Eriksen *et al*., 2013; Free *et al*., 2014; Blettler *et al*., 2017; Bertoldi *et al*., 2021; Chen *et al*., 2021) which generate mostly from secondary sources by fragmentation and disintegration of larger plastic wastes especially in waterbodies that do not have anthropogenic influences and industries around them. Shah *et al*., (2008), Leslie (2014) and Ballent *et al*., (2016) mentioned in their studies that MP fragments and spheroids originate from widely used cosmetic products which not only contain beads but also other forms of MP. Large quantity of fibers and fragments in water is indicative of secondary nature of microplastics (Irfan *et al*., 2020a).

1.3.2 Colour: Studies show that MPs vary in colour for example, white, transparent, black, green, red etc. but white and transparent are the most dominant forms (Pan *et al*., 2019; Couchene *et al*., 2020). Classification of MP on the basis of color through visual inspection may not be a very appropriate way since the color may fade away due to fragmentation, exposure to sunlight and other stresses, or during sample preparation (Hartmann *et al*., 2019). But the colour of the MP particles is of concern to the aquatic life since it is assumed that the white or transparent MP particles are more easily consumed by the aquatic organisms, birds and fauna as compared to colored particles leading to entry of pollutants in the food chain (Prata 2018). Study conducted by Pan *et al*., (2020) showed majority of white MP particles in the river ecosystem that was attributed to long residence time of the MP and their exposure to environmental stresses leading to their weathering. Alfonso *et al*., (2020) stated the abundance of blue coloured MP fibers in the Patagonian lakes ranging in size from 0.2 to 0.4mm. Table 1 shows the colour of the MP particles obtained in various studies around the globe in freshwater ecosystems.

1.3.3 Size: Size of the MP detected in various studies is mainly governed by the equipment and protocol used for sampling. Zhao *et al*., (2018) and Yan *et al*., (2019) reported a high proportion of microplastics smaller than 500mm. Some studies reported occurrence of MP of size ranging between 100 and 1000 mm (Su *et al*., 2016). Large number of studies found very small sized MP in the range of 0.2 to 0.5 mm (Eriksen *et al*., 2013; Alfonso *et al*., 2020; Egessa *et al*., 2020; Gopinath *et al*., 2020; Irfan *et al*., 2020a). Other studies confirmed the presence of MP of size approximately 5-500 μm (Blettler *et al*., 2017; Kataoka *et al*., 2018; Bertoldi *et al*., 2021). Particles found in the sediments were of a wide range in size i.e., from approximately 11-5000 μm (Klein *et al*., 2015; Mani *et al*., 2019).

Cosmetic products, industrial abrasive shot blasting agents utilize MP of very small size i.e. 0.25mm (Issac and Kandasubramanian 2021) thus resulting in primary MP particles in the samples. Small sized MP in the water bodies may also be due to the fact that the waste water treatment plants are not able to retain particles of size less than 0.5mm (Mason *et al*., 2016) and also because the large MP particles undergo fragmentation due to environmental stresses leading to enrichment of small particles in the waterbodies. Thus, tiny MP fragments may be both of primary and secondary in origin. Smaller particles are easily carried by the water current and runoff or may remain suspended in the water column in still water bodies while larger particles may remain in the sediments.

1.3.4 Chemical composition: Studies have shown occurrence of various types of MPs in aquatic environment like acrylic, polyamide (PA), polyester, polyethylene, polypropylene and polystyrene (PS) (Di and Wang 2018; Pivokonsky *et al*., 2018). Most of the papers reviewed showed the presence of PE, PP, PS and PET as dominant forms of MP in their studies (Eriksen *et al*., 2013; Biginagwa *et al*., 2016; Sruthy and Rmasamy 2016; Sighicelli *et al*., 2018; Hendrickson *et al*., 2018; Yin *et al*., 2019; Alfonso *et al*., 2020; Uurasjärvi *et al*., 2020). PE is major component in the manufacturing process of plastic bottles, containers to store food or other items, cosmetic products, in toys, plastic bags, packaging films, straws and various houseware (PlasticsEurope 2018). PP is used in several household and industrial products like food packaging, pipes, parts of automobiles (Pivokonsky *et al*., 2018), bottles, films and coatings (Uurasjärvi *et al*., 2020). PU find a wide application in various products used on a daily basis viz., rubber parts, insulating material, soles of athletic footware (Alfonso *et al*., 2020). PU are also used in the manufacture of foams, adhesives like construction glue, surface coatings or materials used for sealing (Bettler *et al*., 2016). PS is found in packaging applications, cosmetics, and insulation materials while PET is a polymer that is widely used in textile industry, single use plastic bottles, food packaging materials, bags, carpets, non-woven fabrics, fishing nets etc., and tourism industry is one of the major contributors in PET plastic (Alfonso *et al*., 2020). PVC is used to produce plastic bottles, films and cups (Andrady 2011). Epoxy polyester finds use in coatings, adhesives and also as reinforcement material on the boats (Korez *et al*., 2019; Irfan *et al*., 2020a). Food packaging and fishing nets as monofilament have polyamide in them that is a major urban source of MP (Naji *et al*., 2017). Sometimes natural fibers are transformed by addition of additives or mixed with synthetic fibers to impart certain properties to them in such cases identification and characterization of MP becomes difficult. Various identification techniques are employed in the identification process like, Raman spectroscopy, Fourier Transform Infrared spectroscopy, Pyrolysis gas chromatography mass spectrometry, etc. According to Alfonso *et al*., (2020), evaluation of the blue or black fiber becomes difficult with Raman polymer identification as the SRCF (Synthetic regenerated cellulosic fibers) used in the textile industries made from natural fibers are altered by addition of artificial additives (like dyes, bleaching agents, flame retardants, light stabilizers etc.), thus the Indigo Blue fibers may not necessarily be of synthetic origin. Nonetheless, these may be treated as MP (POP) since they tend to persist in the aquatic ecosystems due to their crystalline structure and risks associated with the chemical additives. Most of the studies confirmed the presence of almost all major forms of MP like PP, PE, PMMA, PVC, PS, and PET etc., while Alfonso *et al*., (2020) have reported low concentrations of PP and PS in the lakes from the Argentine Patagonian Region. Pan *et al*., (2020) studied MP pollution in Zhangjiang River and revealed that MP was mainly composed of PP and PE. Yan *et al*., (2019) reported presence of PA, cellophane, PP, PE, and non-microplastic particles which were found to be composed of plastics or additives, in Pearl River, China.

Some studies show association between the colour and the polymer type of the MP. Black coloured MP are often associated with PU that may come from the wear and tear of tires of vehicles, shoes, protective coatings, while amber-coloured particles may be resins containing PS used in the ion exchange process of water purification, medical or industrial purposes (Bettler *et al*., 2016; Alfonso *et al*., 2020).

2. BEHAVIOUR OF MP IN FRESHWATER BODIES

Occurrence of MP in the freshwater systems is of great concern since the freshwater systems sustain most of the human settlements. They are source of drinking water and food to large number of organisms as well as humans all over the world and sustain the life and livelihood of millions of people. They play ecologically significant role since they are located upstream and act as suppliers of water, nutrients, and influence dynamics, hydrology and other characteristics of estuaries and oceans (Pan *et al*., 2020). They may also act as carriers of pollutants to the systems downstream. The freshwater systems behave in a different way as compared to the marine ecosystems due to difference in their hydrology, physicochemical characteristics, mixing characteristics, location etc., thus affecting the characteristics, abundance and distribution of pollutants (Pan *et al*., 2020). Atugoda *et al*., (2021) enlisted five processes that MP undergo when they enter the aquatic ecosystems viz., sinking, settling, remobilization, advection, and dispersion. The lateral transport of MP particles along with the water flow or currents that is greatly impacted by average flow velocity is called advection, while dispersion is multidirectional flow of the MP particles and is impacted by turbulence in water bodies (Atugoda *et al*., 2021) and both these movements depend on wind velocity, type and depth of the water body, bottom topography as well as seasonal changes (Eerkes-Medrano *et al*., 2015).

The density of MP particles is lower than that of the seawater (i.e. 1.02 g/cm^3), so the polymers like PE and PP are prevalent in almost all marine biotic components in abundance (Veerasingam *et al*., 2020). When MP enter the water bodies a major portion may be found floating on the surface layers (Pivokonsky *et al*., 2018), but denser MP particles may submerge and several studies have proved their presence in the sediments of fresh water bodies (Andrady 2011; Di and Wang 2018; Chouchene *et al*., 2021; Laermanns *et al*., 2021) even though a substantial amount remains suspended across the water column (da Costa *et al*., 2016; Leslie *et al*., 2017). In freshwater ecosystems re-mobilization of MP may occur easily from the sediments because of their low density (Waldschläger and Schüttrumpf, 2019). Seasonal variation also affects the microplastic abundance. MP may be remobilized due to erosion at the time of flooding of lakes and rivers in rainy seasons (Hurley *et al*., 2018; Yan *et al*., 2019).

MP have tendency to associate with chemicals making them more harmful pollutants (Smith *et al*., 2018). According to Rochman *et al*., (2013), it has been observed that the MP in the oceans have the ability to store various types of persistent organic pollutants (POPs) like PAHs (polycyclic aromatic hydrocarbons), PCBs (polychlorinated biphenyls), and also organochlorine pesticides like DDT (dichloro diphenyl trichloroethane), HCB (hexachlorobenzene). These substances are very harmful in nature and have more affinity for microplastic particles than water as explained by their higher concentrations on the MP surface in comparison to their concentrations in surrounding water (Andrady 2011; Rochman *et al*., 2013).

2.1 Microplastic behavior in Lake ecosystem

2.1.1 Lake water column: It has been observed in many studies that MP concentration in lake is correlated to its proximity with urban, residential, industrial and densely populated areas (Sruthy and Ramasamy 2016; Irfan *et al*., 2020b). Distribution and abundance of MP in a lake depends on anthropogenic activities or presence of dam around it, as well as total surface area, geographical, topographical features, or internal currents of the lake (Cole *et al*., 2011; Wang *et al*., 2017; Di and Wang 2018) (see Table 1).

Distantly situated lakes are mainly oligotrophic in nature their clear water allows UV radiations of the sun to penetrate into deeper layers as compared to the eutrophic lakes leading to fragmentation of plastic debris and generation of microplastics (Andrady *et al*., 2011; Free *et al*., 2014). But this phenomenon may not occur in case of lakes situated in colder regions, as the presence of ice cover on water prevents thermal/UV degradation of plastics (Free *et al*., 2014). Most of the developmental activities take place around fresh water bodies hence they become potential carriers of pollutants. Just as the microplastic pollution has been reported in the remote seas of the world similarly remotely situated lakes also show high MP concentration than some densely populated Lakes. In a study conducted on lake Winnipeg, Canada Anderson *et al*., (2017) reported elevated levels of MP despite of low population density around it as compared to other lakes, the reason for this anomaly was attributed to the plastic consumption pattern of population residing near Lake Winnipeg and the freshwater rivers flowing in it that enable long-range transport of MP acting as a secondary source. The lakes in rural or remote areas show high MP concentration due to absence of proper waste management system, lack of plastic waste recycling facilities, and unmanaged human activities like tourism, fishing washing etc. (Yin *et al*., 2020).

The freshwater reservoirs and lakes have different residence time, and that affects the pollutant load in them. Lakes having high residence time mostly act as a sink and pool of MP pollutants (Nel *et al*., 2018). For instance, in Lake Hovsgol, Mongolia, a high MP concentration was observed by Free *et al*., (2014), due to its long residence time i.e., 500-600 years while the Laurentian Great lakes like Lake Eire, Lake Michigan and Lake Ontario that have low residence time ranging from 2 to 38 years are supposed to spread pollutants to the oceans and other connected ecosystems (Eriksen *et al*., 2013; Nel *et al*., 2018).

2.1.2 Lake sediment: The higher residence time of MP in water increases its biofouling rate and sedimentation. Biofouling rate depends upon residence time of MP in water, the trophic state, surface-to-volume ratio of MP and nutrient concentrations (Alfonso *et al*., 2020). Thus, lakes that have high nutrient concentration, high water residence time also have high levels of MP in the sediments. Studies confirm that sedimentation of MP occurs with ease in the environments with less energy and weak hydrodynamics i.e., slow moving water courses with minimum disturbances, less wave action (Ballent *et al*., 2016). Such conditions exist in harbours and lagoons and thus there is more accumulation of MP in these areas with no or little resuspension events (known as the Harbouring Effect). Factors other than harbour effect, that influence the distribution and abundance of MP include random fluid flows, presence of obstructing structures, variations in topography, spatial extent of the watershed, roughness, type of vegetation and nature of substratum (Vianello *et al*., 2013; Ballent *et al*., 2016). Hindrance in the path of river or low slope near the mouth of river, reduces the rate of water flow causing more deposition of MP in the upstream region and subsequently decrease in the MP at the mouth of river and in lake shores. Presence of a dam on rivers affects the discharge dynamics and increases the residence time of MP favoring its settlement/sink in the sediments. Density and shape of MP also influences the pattern of their distribution (Ballent *et al*., 2016). Plastic density of most forms (like PP, HDPE, LDPE, some PS) is less than the density of freshwater (with the exception of PET, PVC, PA some forms of PS), indicating that it should float on the water surface but studies have reported occurrence of MP in deep sediments possibly due to increase in density by biofouling, by adsorption of natural substances, fecal matter, or due to inorganic fillers added during manufacturing process (Andrady 2011; Cole *et al*., 2011; McCormick *et al*., 2014; Lambert and Wagner 2018).

Table 1: MP abundance and characteristics in surface water of lake ecosystem

S. No	Location	Sampling method	Chemical composition	Dominant size	Dominant shapes	Dominant Colour	Average concentration	Range Particles/km^2	Reference
1.	Laurentian Great Lakes, US	Manta trawl	PE, PP	0.355–0.999 mm	Pellet>Fragments> foam>films> line	-	43,157 MP/km^2	456 to 4,66,205	Eriksen *et al.*, (2013)
2.	Lake Hovsgol, Mongolia	Manta trawl	Not reported	0.355–0.999 mm, 1.00–4.749 mm	Fragments > films>fiber> foam> pellet	-	20,264 MP/km^2	997 to 44,435	Free *et al.*, (2014)
3.	Taihu Lake, China	Plankton net	Cellophane> PE> Terephthalate, PL, Terephthalic acid, PP	100 to 1000 µm	Fiber> Fragment > Film > Pellet	Blue items	-	0.01x10^6 to 6.8x10^6	Su *et al.*, (2016)
5.	Lake Winnipeg, Canada	Manta trawl	Not reported	< 5 mm	Fibers>Films>Foam	Not reported	193,420 MP/km^2	53,000 to 748,000	Anderson *et al.*, (2017)
6.	Italy (Lake Maggiore, Lake Garda and Lake Iseo)	Manta trawl	PE (45%), EPS(18%), PP (15%), PVC, PL	1 to 5mm	Fragments (73.7%)> Filaments (3.4%)> Sheets (2.7%)> Pellets (2%)	Not reported	-	4000 to 57000	Sighicelli *et al.*, (2018)
7.	Western Lake Superior	Manta tow net	PVC> PP>PE>PET>CPE> PS> PDMS> Didecyl phthalate plasticizer resin	250 µm to 4.0 mm	Fibers> fragments> films> Beads/spheres> foams	Not reported	-	0 to 1,10,000	Hendrickson *et al.*, (2018)
8.	8 major lakes, Changsha, China	Grab sampling	PP(33.75%),PE(27.5%), PS(13.75%),PET(11.25%),PA(7.5%), PVC(3.75%)	2 mm (89.5%)	Line, Film, Foam, Fragment	Transparent, black, white, red, blue	-	2425 to 7050 particles /m^3	Yin *et al.*, (2019)
9.	9 lakes in	Horizonta	PET(38.3%),	0.2 -<0.4 mm	Fibers>foam>	Blue (42%),	0.9 MP/m^3	0.3 to 1.9	Alfonso *et al.*,

	Argentine Patagonia, South America	l trawling	PU(11.8%), PP(2.9%), PS(2.9%)		fragment> film	black (37%)		particles /m^3	(2020)
10.	Rawal Lake Islamabad, Pakistan	Bulk surface water sample	PE, PP, PEST, PET, PVC	< 1 mm	Fibers, Fragments	Blue, red, black, transparent	0.142 MP/0.1 L	0.18 to 0.11 particles /0.1L	Irfan *et al.*, (2020b)
11.	Northern Lake Victoria	Floating manta net	PE>PP>PS>PES	0.3-4.9 mm	Fragment (36.7%), flakes (25.0%), filament (23.0%), film (15.0%), foam (0.3%)	-	-	2,834 to 329,167 particles/km^2	Egessa *et al.*, (2020)
12.	Red Hills Lake, Tamil Nadu, India	Plankton Net	HDPE, LDPE, PP, PS	1 -2 mm	fibers (37.9%), fragments (27%), films (24%), pellets (11.1%)	White (65%), green (19%), blue (13%), red (3%)	5.9 MP/L	-	Gopinath *et al.*, (2020)
13.	Lake Kallavesi, Finland	Manta Trawl	PE> PP> PET> PMMA>PVC> PS	20-300 µm	Fibers>Fragments	White, blue, red, brown, black, green	0.27 MP/m^3	0.66 to 0.037 particles /m^3	Uurasjärvi *et al.*, (2020)
14.	Reservoir Jatiluhur, Indonesia	Manta trawl	PE (54.73%), PP (45.27%)	1000-5000 µm	Fragments and linear	Not Reported	$2.58x10^5$ MP/km^2	$0.71x10^4$ to $4.59x10^5$ particles/km^2	Ramadan and Sembiring (2020)
15.	Lakes Mead and Mohave, USA	Towing of microplastics net	-	355–1,000 µm (73.1%); 1,000–5,600 µm (26.5%)	Fibers (68.9%), fragments (15.6%), films (8.9%), foams (6.5%)	Clear (33.4% average), white (18.7%), black (17.1%), blue (14.7%)	-	0.44 to 9.7 particles/ m^3	Baldwin *et al.*, (2020)
16.	OX-Bow Lake Yenagoa, Nigeria	Bulk surface water sampling	Dry season= PET (72.6%), PVC (10.9%), HDPE (7.7%), PP (6.3%), LDPE (1.2%) Rainy season= PVC	Dry season= 1–3 mm (74.9%), 3–5 mm (14.1%) Rainy	Fibers, beads, fragment, pellet, films and flakes	Black, yellow, green, red, blue, white, purple	-	Dry season= 1004 to 8329 particles/ m^3 Rainy season= 201–8369	Oni *et al.*, (2020)

			(81.5%), PET (2.6%), PA (1.7%), LDPE (0.9%), PS (0.1%)	season= 0.51–1 mm (89.1%)				particles/m^3	
17.	Lake Sassolo, Switzerland	Grab sampling	PE (76.9%), PP (23.1%), PB, PBMA, PET, PS	63 µm - 125 µm	Fibres	-	2.6 MP/L	-	Negrete *et al.*, (2020)
18.	Lake Simcoe, Ontario, Canada	Grab sampling & Manta trawl	PE (41%), PP (22%), PU (7.7%), PEST (7.7%)	>125 mm	Fibers (82.4%) fragments (5.9%), fiber bundles (5.9%) foams (5.9%)	Blue (47%), green (12%) red (12%), silver, white, yellow, black and clear	0.25 MP/L in grab sample	0 to 0.7 particles/L in grab sample; 0.4–1.3 particles/ m^3 in manta trawl	Felismino *et al.*, (2021)
19.	Lake Guaíba in southern Brazil, South America	Manta Net	PP (54.5%), HDPE & LDPE (43.3%), PTFE (0.5%), PA (0.5%), PU (0.5%), PS (0.5%)	100–250 µm	Fragments, Fibres, Microbeads	White/Transparent (31.2%), Red (29.3%), Blue, Green, Black, Yellow		11.9 to 61.2 particles/m^3	Bertoldi *et al.*, (2021)
20.	Phewa Lake, Nepal.	Steel bucket	Not reported	<1 mm	Fibers, Films, Fragments, Foam	Transparent> Black> Red> Blue> White> Green> Yellow> Purple	Winter season= 2.96 MP/L Rainy season= 1.51 MP/L	Winter season= 0.8 to 8 particles/L Rainy season= 0.4 to 2.8 particles/L	Malla-Pradhan *et al.*, (2022)
21	Sürgü Dam reservoir, Malatya, Turkey	Steel bucket	PP, PS, PET, PE	1-2 mm	films, fragments, fibers, and foams	Black, transparent, white, blue, purple, red, green, grey	-	106.7 to 220 particles/m^3	Turhan (2022)

MP= Microplastic, PE =Polyethylene, PP=Polypropylene, PET=Polyethylene terephthalate, PES=Poly ether sulfone, PMMA=Polymethyl methacrylate, PVC=Polyvinyl chloride, PS=Polystyrene, PTFE=Polytetrafluoroethylene, PA=Polyamide, PU=Polyurethane, PEST/PL= Polyesters, CPE=Chlorinated polyethylene, PDMS=Polydimethylsiloxane, EPS=Expanded polystyrene, PBMA=Poly (butyl methacrylate), PB=poly(1-butene), HDPE= High-density polyethylene, LDPE= Low-density polyethylene

Table 2: MP abundance and characteristics in sediments of lake ecosystem

	Location	**Sampling method**	**Chemical composition**	**Dominant Size**	**Dominant shape**	**Dominant Colours**	**Average concentration**	**Range**	**Reference**
1.	Vembanad Lake, Kerala, India	Van Veen grab	LDPE >HDPE >PS>PP	<5 mm	Film> foam> fiber/line> pellets	-	252.80 MP/m^3	96 to 496 MP/m^3	Sruthy and Ramasamy (2016)
2.	Lake Ontario	Sediment trap, core and grab sampling	PE (31%), PS (10%), PU (4%), PP (3%), PVC (3%), PSS (3%)	<2mm	Fragments>Fibers > Beads	-	760 MP/kg	20 to 27,830 MP/kg	Ballent *et al.*, (2016)
3.	Taihu Lake, China	Peterson sampler	Cellophane> PE> Terephthalate> PEST> Terephthalic acid>PP	100 to 1000 µm	Fiber> Fragment > Film > Pellet	White, Transparent	-	11.0 to 234.6 MP/kg	Su *et al.*, (2016)
4.	Shore line sediment, Setúbal Lake, Argentina	Quadrat (25 × 25 × 3 cm)	Foam microparticles (EPS)	350 µm	Hard plastic fragments>Fiber>Foam>Film >Line	Transparent, Milky Transparent, Blue, White, Gray, Black, Yellow, Green, Orange	704 MP/m^2	-	Blettler *et al.*, (2017)
5.	Poyang Lake, China	Quadrant (50×50 cm)		<1 mm	Fragments, Films, Fibers, Foam	Blue, white	1134 MP/kgDW	11 to 3,153 MP/kg	Liu *et al.*, (2019)
6.	Hampstead Pond, London, UK	Sediment core sampling	PVC, polysulphide rubber, polyacrylonitrile composites, PS	> 1-mm	Fibers, fragments, foam-like particles, crumpled film	Blue (25%), White (22%), Red (17%), Black (8%), Pink/ purple (3%), Green/ turquoise (2%)	539 MP/kg DW	-	Turner *et al.*, (2019)

7.	Shoreline sediment of Lake Ziway, Africa	Ekman grab sampler	PE, PP, AV> PET, EPR, PUAR	0.1 mm	Fragments, fibers	Transparent White (43%), Blue (36%), Red, Green, Black, Pink	Median = 30,000 MP/m^3	400–124,000 MP/m^3	Merga *et al.*, (2020)
8.	Rawal Lake, Islamabad, Pakistan	Quadrant (15×15 cm)	PE, PP, PEST, PET, PVC	< 1 mm	Fibers, Fragments	Blue, Red, Transparent, Black	1.04 MP/0.01 kg	7 to 15 MP/0.01 kg	Irfan *et al.*, (2020b)
9.	Red Hills Lake, Thiruvalluva, Tamil Nadu	Van Veen grab	HDPE, LDPE, PP, PS	1 mm, 0.3 mm, 2 mm,	Fibers (37.9%), Fragments (27%), Films (24%), Pellets (11.1%)	White (65%), green (19%), Blue (13%), Red (3%)	27 MP/kg	-	Gopinath *et al.*, (2020)
10.	Lakes Mead and Mohave, USA	Ponar sampler	-	355–1,000 µm (63.7%)	Fibers (80.3%), Fragments (8.9%), Films (7.7%), Foams (1.4%)	Clear (37.8%), Black (26.2%), Blue (24.3%), Red (6.5%)	-	87.5 to 1,010 MP/kg DW	Baldwin *et al.*, (2020)
11.	OX- Bow Lake Yenagoa, Nigeria	Grab sampler	Dry season=PET (77.4%), PVC (11.3%), PP (5.9%), PA (1.2%), HDPE (1.1%), PE (0.7%), LDPE (0.5%) Rainy season= PVC (83.9%), PVC UP (5.1%), LDPE (4.2%), PET (3.4%), PE (2.6%), PS (0.3%), PP (0.1%)	Dry season= 1–3 mm (74.9%) Rainy season= 0.51–1 mm (89.1%) (0.02–5 mm)	Fibre, Beads, Fragment, Pellet, Films, Flakes	Black, Yellow, Green, Red, Blue, White, Purple	-	Dry season = 347 to 4031 MP/kg Rainy season= 507 to 7593 MP/kg	Oni *et al.*, (2020)

12.	Lake Simcoe, Ontario, Canada	Petite Ponar	PS (4.3%), PE (4.3%), acrylic (2.1%), nylon (2.1%), PE/PP copolymer (2.1%)	> 125 mm	Fibers (89.2%), Fragments (5%), Fiber Bundles (2.5%), Spherical Microbeads (2.5%), Films (0.8%)	Blue (46.7%), Black (20.8%), Red (11.7%)	372 particles/kg DW	8 to 1070 MP/kg	Felismino *et al.*, (2021)
13.	Anchar Lake, Kashmir Valley, Northwest Himalaya	Van Veen Grab Sampler	PA (96%), PET (1.4%), PS (1.4%), PVC (0.9%), PP (0.7%)	0.3 to 1 mm (53%)	Fibers (91%), Fragments/Films (8%), Pellets (1%)	White(51%), Red (26%), Black (8%), Blue (8%), Yellow (5%), Green (2%)	606 MP/kg of DW	233 to 1533 MP/kg of dry weight	Neelavannan *et al.*, (2022)
14.	Sürgü Dam reservoir, Malatya, Turkey	Ekman grab	PET, PE, PP, PA	0.2-1 mm	Films, Fragments, Fibers, Foams	Black, Transparent, White, Blue, Purple, Red, Green, Grey	-	760 to 1440 MP/m^2	Turhan (2022)

MP= Microplastic, DW= Dry weight, PE =Polyethylene, PP=Polypropylene, PET=Polyethylene terephthalate, PVC=Polyvinyl chloride, PS=Polystyrene, PTFE=Polytetrafluoroethylene, PA=Polyamide, PU=Polyurethane, PEST/PL= Polyesters, CPE=Chlorinated polyethylene, PDMS=Polydimethylsiloxane, EPS=Expanded polystyrene, PBMA=Poly (butyl methacrylate), PB=poly (1-butene), HDPE= High-density polyethylene, LDPE= Low-density polyethylene, AV=Alkyd-varnish, EPR =Ethylene-propylene rubber, PUAR=Polyurethane acrylic resin, PSS=polystyrene sulfonate, EPS=expanded polystyrene, PB=poly (1-butene)

Due to an increase in the density of the MP they tend to settle down behaving like the mineral sediments. Eriksen *et al*., (2013), reported abundance of microbeads in the water column and less abundance in the sediments due to their low density while Irfan *et al*., (2020b) reported more of fibers and fragments in the sediments of Lake View Park. This may be due to the high inflow of domestic waste, and use of ropes, nets, fishing gears in recreational shipping (Su *et al*., 2016; Wang *et al*., 2017). Most common type of plastic polymers found in sediments include PE, PS, polyurethane (PU), PP, PA and PVC in sediment (Imhof *et al*., 2013; Ballent *et al*., 2016; Anderson *et al*., 2017). Type of plastic found may differ in different water bodies due to variable input sources. Imhof *et al*., (2013) found higher concentrations of low-density polymers (like PE, PP, PS) and lesser concentrations of PVC and PA (polyamide) in the sediment samples of lake Garda, Italy while Ballent *et al*., (2016) found the presence of PET in sediment samples of Lake Ontario (Table 2).

2.2 Microplastic behavior in the River Ecosystem

2.2.1 River water: River ecosystems behaves in different way as compared to lake ecosystem since the river dynamics are more active. The turbulent water flow in river expedites the plastic disintegration process leading to formation of microplastic, especially in small rivers or streams with high rate of water mixing characteristics. Hence, MP and other pollutants may have different settling rates. Pollutants in these ecosystems have low residence time as compared to the lentic systems thus they have more potential to disperse pollutants and have connection with the seas and oceans. Rivers show much variation both vertically as well as horizontally in terms of water currents, sediment load and base flow. The rivers also differ from the lakes, reservoirs, oceans in having disproportionately high sediment to water column ratio (Nel *et al*., 2018). Dynamic changes in the river flow and the saline water intrusion due to wave and tide action also affects the abundance and distribution of MP in rivers (Pan *et al*., 2020). Thus, separate studies on the effect of MP distribution due to estuary effect, and saline water inflow are required. MP abundance and accumulation is also influenced by particle characteristics, river flow, depth of water column, substrate type or river bottom topography (Klein *et al*., 2015), distance and intensity of its source, urban runoff and other hydrological parameters of the river (Campanela *et al*., 2019; Yan *et al*., 2019). The density and properties of MP particles may change in rivers due to formation of biofilms on their surface as a result of their high residence time and this ultimately affects biofouling (Horton *et al*., 2017; Laermanns *et al*., 2021).

Campanela *et al*., (2019), reported that there is great variation in the temporal and spatial MP concentrations in their study and thus monitoring of these variations is important to find out the change in the MP concentrations, its fragmentation process and ultimately to detect the effect on the ecosystem. Kataoka *et al*., (2018) have proved that there is a significant relation between MP (measured in numbers as well as mass) and BOD proving that the polluted rivers are likely to have more concentration of MP than the rivers with good water quality, thus the inflow system and sources of MP in rivers is similar to that of other river pollutants (Table 3).

Studies indicate that MP concentration depends upon the human activities around the river basin and there is a significant correlation between its concentration and urbanization and human population (Lebreton *et al*., 2017; Kataoka *et al*., 2018). Since rivers are more in contact with the human settlement hence, they have diverse sources of microplastics like industrial emissions, land use, agricultural activities, tourism, poor solid waste management etc. Just like lakes, the rivers also receive waste water coming from urban areas as one of the major sources of MP (Yan *et al*., 2019). Cellophane extensively used in kitchens, packaging materials, cigarette wrapping, and in production of rubber and fiberglass products can be a potential source of MP in rivers if not disposed properly (Yang *et al*., 2015; Castillo *et al*., 2016).

According to Klein *et al*., (2015) river ecosystems are highly dynamic therefore they may act as local sink of pollutants that may easily get washed-out due to various factors like river flow, seasonal variations, climatic extremes etc., and this may be the reason behind lack of correlation between presence of industries, urban areas, high population along the rivers and MP abundance in some studies.

Table 3: Microplastic in river water

S.No.	Description	Sampling method	Chemical composition	Size range	Dominant type	Average Concentration	Range	Reference
1.	Rhine river, Europe	Manta trawl	PS (29.7%), PP (16.9%), other types (13.6%), acrylate (9.3%), PEST (5.1%) PVC	300–1000 µm	Opaque Spherules (45.2%), Fragments (37.5%), Transparent Spherules (13.2%), Fibres (2.5%) Others (1.1%)	892,777 MP/km^2	1,940 to 17,930 MP/ 1,000 m^3	Mani *et al.*, (2015)
2.	Saigon River, Southern Vietnam	Net (mesh size: 300µm)	PEST (70%), PET (9%), PE (5%), PP (4%), PE-PP copolymer (4%), Rayon (4%)	50-250 µm	Fibres>fragments	-	270,000 to 519,000 MP/m^3	Lahens *et al.*, (2018)
3.	Lam Tsuen River, Hong Kong, China	Nylon net (mesh size: 0.27mm)	PP/EPR (70.0%)> PP (15.5%)> PE (7.6%)> LDPE (5.1%)	0.355 to 2000 mm	Fibres (48.7%) Films (46.5%) Foams (29.6%)	7.428 MP/m^3 (Mean)		Cheung *et al.*, (2018)
4.	29 Japanese rivers	Plankton nets	PE>PP>PS	335 µm	Fragments, resin pellets	12 MP/m^3	-	Kataoka *et al.*, (2018)
5.	Ofanto river, Italy	Plankton nets	PE	300-5000 µm	Fragments>flakes>lines >fibres> pellets		0.9 to 13 MP/m^3	Campanale *et al.*, (2019)
6.	Ciwalengke River, Majalaya, Indonesia	Grab sampling	Polyester and nylon	50 -100 µm	fiber (65%), fragment (35%)	5.85 ± 3.28 MP/liter		Alam *et al.*, (2019)

7.	Pearl River, Southern China	Water sampler	PA (26.2%), Cellophane (23.1%), PP (13.1%), PE (10.0%), Vinyl acetate copolymers (VACs), PVC	<0.5 -5 mm	Film> Granule> fiber	19,860 MP/m^3	7850 to 53,250 MP/m^3	Yan *et al.*, (2019)
8.	Ravi river, Lahore, Pakistan	Surface water sampling		300 µm– 5 mm	Fragments (56.1%), Fibers (38.6%), Sheets (2.5%), Foams (2.2%), Beads (0.6%)	2074 ± 3651 MP/m^3		Irfan *et al.*, (2020a)
9.	Zhangjiang River, China	Bulk sampling, manta net	PP, PE, PS, PES, PET, PE-PP blends	0.5–1 mm (32.8%) (0.3–5 mm)	Fragment (42.9%), Fiber (18.5%), Pellet (17.6%), Line (13.8%), Film (4.1%), Foam (3.1%)	246 MP/m^3 (Mean)	50 to 725 MP/m^3	Pan *et al.*, (2020)
10.	Elbe and Mulde rivers, Germany Europe	Apstein plankton net (mesh size: 150 & 300 µm)	PE>PS>PP	50- 500 µm	Spheres> Films> Fragments> Fibers		0.33 to 1.19 mg/m^3	Laermanns *et al.*, (2021)

MP= Microplastic, DW= Dry weight, PE =Polyethylene, PP=Polypropylene, PET=Polyethylene terephthalate, PES=Poly ether sulfone, PVC=Polyvinyl chloride, PS=Polystyrene, PTFE=Polytetrafluoroethylene, PA=Polyamide, PU=Polyurethane, PEST/PL= Polyesters, CPE=Chlorinated polyethylene, PDMS=Polydimethylsiloxane, EPS=Expanded polystyrene, PBMA=Poly (butyl methacrylate), PB=poly (1-butene), HDPE= High-density polyethylene, LDPE= Low-density polyethylene, AV=Alkyd-varnish, EPR =Ethylene-propylene rubber, PUAR=Polyurethane acrylic resin, PSS=polystyrene sulfonate, EPS=expanded polystyrene, PB=poly (1-butene)

Table 4: Microplastic abundance in river sediments

S. No.	Description	Sampling method	Chemical composition	Size range	Dominant type	Average Concentration	Range	Reference
1.	Rhine and Main rivers, Germany	Random sampling	PS >PE>PP>PET, PVC, ethylene vinyl acetate, EPDM, PA, acrylic-based polymers	63- 200 µm	Fragments, Spheres, Fibers, Pellets	-	Rhine: 228–3763 MP/kg Main: 786 - 1368 MP/kg	Klein *et al.*, (2015)
2.	River Tame, West Midlands, UK	Random sampling	PE (50%), PVC, (30%), polymethyl methacrylate (20%)	63 µm-1 mm	Fragments> Fibres	165 MP/kg	-	Tibbetts *et al.*, (2018)
3.	Austral temperate river, South Africa	Quadrat	-	63 µm- 5000 µm	-	Summer = 6.3 MP/kg Winter= 160.1MP/kg		Nel *et al.*, (2018)
4.	Rhine river, Germany	German diving bell vessel Carl Straat	Acrylates/PU/varnish cluster, CPE, EPDM, PEST, PE	11-5033 µm	-	-	0.26 to 11.07× 10^3 MP/kg	Mani *et al.*, (2019)
5.	Ciwalengke River, Majalaya, Indonesia	Ekman grab sampler	Polyester, nylon	1000 - 2000 µm	Fiber (91%), Fragment (9%)	3.03 MP/100 g dw	-	Alam *et al.*, (2019)
6.	Elbe and Mulde rivers, Germany, Europe	Van Veen grab sampler	PS>PE> PP	50-1000 µm	Spheres>Fragments>Films>Fibres	-	0.8 to 1 mg/kg	Laermanns *et al.*, (2021)

MP= Microplastic, PE =Polyethylene, PP=Polypropylene, PET=Polyethylene terephthalate, PVC=Polyvinyl chloride, PS=Polystyrene, PTFE=Polytetrafluoroethylene, PA=Polyamide, PU=Polyurethane, PEST/PL= Polyesters, CPE=Chlorinated polyethylene, EPDM= ethylene propylene diene rubber .

Yan *et al*., (2019) observed variation in the abundance of MP seasonally also and found that it was affected by the rainy season in Guangdong Province, China. Similarly, Pan *et al*., (2020) mentioned that storms, typhoons and variability in local climatic conditions may introduce more MP in the riverine ecosystems that may in turn significantly increase its amount in the coastal areas and the banks of the rivers.

2.2.2 River sediment: Study conducted by Nel *et al*., (2018) in an African river system showed that the MP abundance in river sediments varied considerably in different season, which may be attributed to the arid climate of the region that causes fluctuation in the river water level in summers and in winters. It was observed that during winter season MP concentration was much higher due to reduced water inflow. Thus, the rivers in arid regions are not potential sinks of MP and they act as temporary reservoirs of pollutants ultimately transporting them to the oceans mainly due to their varying hydrodynamics showing a temporal variation in the concentration (Klein *et al*., 2015; Nel *et al*., 2018). Rain events lead to increase in the MP pollution in the river catchment as indicated by Faure *et al*., (2015) in an investigation done around urban area of Rhone catchment where an increase of upto 150 times in MP concentration was reported.

Distribution of MP particles is affected by various external factors like MP particle characteristics, river water flow, depth of water, type of river sediment/substrate and bottom topography (Klein *et al*., 2015; Nel *et al*., 2018). River flow was found to be significantly associated with the sediment MP concentration just like substrate embeddedness and SOM (sediment organic matter) in a study conducted by Nel *et al*., (2018) in Bloukrans River system, in the Eastern Cape South Africa.

MP characterization in various lake sediments showed the presence of various types of plastics. Irfan *et al*., (2020a) in their investigation reported abundance of fragments (83.1%) in the sediments of Ravi River of Lahore, Pakistan followed by fibers, foams, sheets and beads the sediment samples. Similar results were obtained by Wessel *et al*., (2016) in the estuarine sediment samples collected from the Gulf of Mexico where fragments (47.8%) and fibers (22.3%) had high relative abundance. Klein *et al*., (2015) reported contamination of German rivers sediment, with fragmented microplastics ranging between 228–3763 particles/kg (Table 4). The high concentration of MP in the sediments of the rivers poses a serious threat to the organisms dwelling in the sediments even when the rivers act as temporary sinks, the lifecycles of most of the bottom feeders may get affected adversely (Besseling *et al*., 2017; Nel *et al*., 2018).

3. HEALTH IMPACTS ON FRESHWATER ORGANISMS

Microplastics, due to their small size, persistent, resistant and hydrophobic nature tend to create direct as well as indirect harmful impacts on living organisms. Plastic polymers have a very broad range of densities, shapes and sizes thus affecting their dispersion and behavior in the surface layers, water column or sediments of the water bodies (de Sa *et al*., 2018). Organisms residing in various zones of the water bodies are therefore exposed to and affected by MP (Thompson *et al*., 2009; Cole *et al*., 2011). MP formed by degradation of low-density plastics such as PE and PP tend to float on the water surface unless their density increases due to biofouling caused by association with microorganisms and algae or due to ingestion by organisms (Issac and Kandasubramanian 2021). Plastic debris formed from high density plastics viz., PET, PS, cellulose acetate, polymer with fillers, tend to settle in the sediments thus affecting the bottom feeders (Driedger *et al*., 2015).

It is difficult for the aquatic organisms to differentiate between MP and food particles due to similarity in their size and color, thus making them bioavailable and bioaccumulate in the food chain. Due to minute size of plastic particles, their entry and deposition in the living tissues is easy and eventually causes obstruction and disruption in the biological processes (Campanale *et al*., 2020; Issac and Kandasubramanian 2021). Hence, color and size of MP particles play very crucial role in determining their bioavailability. Studies have shown that MP have the ability to accumulate in the intestines, gills, liver, gut of freshwater species (Kokalj *et al*., 2018). Studies indicate that MP can readily enter the food chain and transfer through various trophic levels thus posing serious threat to living organisms especially to those found at the initial levels of food chains like planktons, small fishes, birds etc. (Alfonso *et al*., 2020).

MP have been reported in oysters (Li *et al*., 2018a), freshwater duck mussel (*Anodonta anatine*) in a Swedish river (Berglund *et al*., 2019), freshwater fish species of rivers like gudgeons (*Gobio gobio*) in France (Sanchez *et al*., 2014), chub (*Squalius cephalus*) in Paris (Collard *et al*., 2018), and roach (*Rutilus rutilus*) in Thames river UK (Horton *et al*., 2018), Gizzard shad (*Dorosoma cepedianum*) and largemouth bass (*Micropterus salmoides*) in drinking water reservoirs in an agricultural landscape of Illinois (Hurt *et al*., 2020), Nile tilapia (*Oreochromis niloticus*) and catfish (*Bagrus bayad*) in river Nile, Egypt (Khan *et al*., 2020). Pazos *et al*., (2017) conducted a study to detect MP in gut of 11 species of coastal freshwater fish found in the Rio de la Plata estuary, Argentina and found that MP was present in the gut content of 100% studied fish population and MP fibres constituted the major MP type (Table 5).

Laboratory based exposure studies have been conducted to find out the possible toxic impacts of ingestion of MP on some freshwater aquatic species. A study conducted on crustacean planktonic species *Daphnia magna* showed accumulation of MP in the gut but no toxic impacts on physiological and reproductive health were observed (Kokalj *et al*., 2018). Laboratory based study conducted on Zebrafish (*Danio rerio*) showed accumulation of MP in the different parts of zebrafish i.e. gut, gills, liver and caused intestinal damage, inflammation of liver, developmental defects (Lei *et al*., 2018; Pitt *et al*., 2018; Qiao *et al*., 2019).

Issac and Kandasubramanian (2021) enlisted three lethal effects associated with MP:

a) *Biological effects related to ingestion:* MP have been reported to produce toxic effects like, damage and inflammation of mucosal layer of intestines ultimately leading to metabolic disorder and the role of MP fibers is stronger as compared to the fragments and other forms in inducing intestinal toxicity in fish (Qiao *et al*., 2019). Presence of MP in the living tissues lead to reduction in growth rate and reproductive capacity, pathological and oxidative stresses mainly due to their association with toxic chemicals (Yan *et al*., 2019). The risks associated are likely to increase with the rise in the number of MP intake leading to hampered development in organisms (Horton *et al*., 2018). Several studies have confirmed that ingestion of MP by freshwater organisms is associated with physical impacts like irritation in gut, obstruction of the digestive tract and feeding organs of invertebrates, stress, tissue injury, bioaccumulation, entanglement in tissues, tumor development, restricted enzyme and hormone production, restrictive food uptake ultimately affecting immunity, metabolic activities, normal growth, reproduction and energy balance (Sanchez *et al*., 2014; Biginagwa *et al*., 2016; Rist and Hartmann, 2018). Blettler *et al*., (2017) suggested that mainly white and transparent MP are subjected to ingestion by visual predator fish in the Setúbal Lake, and this risk is greater in the flooding stage when there is enhanced mixing of MP from sediments and beaches due to turbulence and floatation.

b) *Toxic effects of the additives*: Plastic products incorporate hazardous substances as additives that are added to fulfil some functional role like stabilizers, biocides, flame retardants, lubricants, plasticizers, antistatic agents, curing agents, foaming agents, slip agents, etc.; or as colorants like pigments, soluble azocolorants, etc.; and also, as reinforcement material like glass or carbon fibers etc. These substances are merged with plastic during manufacturing process and they easily enter living tissues leading to their bioaccumulation. The extent of additives used differs in different types of plastics thus showing variable intensities of toxic effects. Sometimes in the plastic manufacturing processes, metals are also incorporated in additive agents, which may act as catalysts, or stabilizers or pigments (Blettler *et al*., 2017).

c) *Effects of absorbed pollutants*: MP particles due to their large surface areas, hydrophobic and resistant nature cause pollutants to adhere to their surface allowing transport and ingestion of these pollutants at faster rates. Some commonly found contaminants on the MP include PCB, DDT, organo-chlorinated pesticides, PAH, chlorinated benzenes as well as hexachlorocyclohexane (O’Donovan *et al*., 2018). MP particles collected from the surface waters of the Lake Erie in North America were found to be contaminated with PAH and PCB which are potent carcinogens and teratogens (Driedger *et al*., 2015).

Table 5: Microplastic in freshwater organisms

S.No.	**Organisms**	**% Affected**	**Number of items per organism**	**Body Part affected/studied**	**Size, Shape, Colour**	**Polymer type**	**Location**	
1.	Gudgeon (*Gobio gobio*)	12		Digestive tract	500-1000 µm Hard, pellets, colored fibers, transparent fibers,	-	French rivers	Sanchez *et al.*, (2014)
2.	Nile perch (*Lates niloticus*)	55		Gastrointestinal tract		PE, PU, PEST, PE/PP, copolymer silicone rubber	Lake Victoria, Tanzania	Biginagwa *et al.*, (2016)
3.	Nile tilapia (*Oreochromis niloticus*)	35						
4.	Asian Clams	-	0.2 to 12.5 MP/g ww	Soft tissue	100 -1000 µm Fibers; White, transparent	Cellophane, PE, terephthalate, terephthalic acid, PP	Taihu Lake, China	Su *et al.*, (2016)
5.	Chironomid larvae (*Chironomus* spp.)	75-98	0-5.04 MP/mg ww	larvae	63-5000 µm	-	-	Nel *et al.*, (2018)
6.	Zebrafish (*Danio rerio)*		-	Intestine mucosal damage	4-40 µm; Fibers (8.0 µg/mg), Fragments (1.7µg/mg), Beads (0.5µg/mg)	PS	Wuhan, China	Qiao *et al.*, (2019)
7.	*Clarias gariepinus*	41	-	Gastrointestinal tracts	0.2-40 mm Fragments (57.5%), fibres (42.5%); Blue (37%), transparent white (36%)	PE, PP, alkyd-varnish (AV)	Lake Ziway, Ethiopia	Merga *et al.*, (2020)
8.	*Cyprinus carpio*	39	-					
9.	*Carassius carassius*	37	-					

10.	*Oreochromis niloticus*	22	-					
11.	Striped bass (pelagic feeder)	-	0–19 MP /organism	Gastrointestinal tract	Fibers (90.7%); clear (37.2%), blue (29.5%), black (17.1%), red (9.3%)	-	Lakes Mead and Mohave, USA	Baldwin *et al*., (2020)
12.	Common carp (benthic feeder)	-	0-16.5 MP /organism					
13.	Quagga mussels	-	2.5-13 MP /organism	Digestive soft tissue	Fibers (80.9%), films (11.4%), fragments (6.3%), foams (1.4%); Clear (42.5%), blue (23.1%), black (17.8%), red (4.9%)			
14.	Asian clams	-	18–105 MP /organism					
15.	White Sucker (*Catostomus commersonii*)	-	519 MP/fish	Gastrointestinal tract	Fibers>fragments; Black, clear, blue, white	PE (24%), PET (20%), PP (18%)	Lake Ontario and Lake Superior	Munno *et al*., (2022)
16.	Brown Bullhead (*Ameiurus nebulosus*)	-	915 MP/fish					
17.	Longnose Sucker (*Catostomus catostomus*)	-	790 MP /fish					
18.	Yellow Perch (*Perca flavescens*)	-	-					
19.	*C. carpio*	43.5	1.48 MP/fish	Gastrointestinal tract	Films, fragments, and fibers; Black, transparent, white, blue, purple, red, green, grey	PP, PP, PET, PP, PE		Turhan *et al*., (2022)
20.	*A. mossulensis*	6.7	1.33 MP/fish					

Various types of plastics can adsorb chemical pollutants in different capacities. For instance, PE and PP have much greater ability to adsorb chemical pollutants as compared to other type of polymers and studies have confirmed that PVC can accumulate chemicals like nonylphenol and triclosan, and may cause physiological dysfunction, disturb the immune system and result in mortality of aquatic organisms (Rochman *et al*., 2013). While PS glass polymer due to presence of a benzene ring shows greater adsorption rates (Alimi *et al*., 2018). Some polymers have more affinity towards highly toxic chemicals than others hence the polymers vary in their ability to affect aquatic organisms and depend upon the type of chemical sorbed and ease with which they are ingested by the organisms. MP are found to be contaminated with persistent organic pollutants (POPs, like PBDE, PCB) by different processes like, absorption, adsorption, and desorption (Crawford and Quinn 2017) and the sorption process is affected by polymer type, polymer density and the nature of pollutant (da Costa 2016). Desorption process causes release of the adsorbed pollutants in the gut of aquatic organisms and enhances leaching of pollutants in the tissues leading to chronic effects. Once the microplastics enters the gut of organism desorption of POPs, a part of MP, occurs at a faster rate while desorption rate in the environment is enhanced by low organic content of the milieu, elevated temperature and lower pH (Bakir *et al*., 2014). Type of chemicals adsorbed, adsorption rate, mode of their action on freshwater organisms is influenced by size and type of microplastic, environmental temperature and method of transfer. Several polymers also have the ability to adsorb heavy metals on their surfaces (Turner and Holmes 2015). Gopinath *et al*., (2021) reported adsorption of many metals like Al, Fe, Mg, Ca, Na, Si, Ti, K on MP particles obtained from Red Hill lakes, India. Similarly, Chouchene *et al*., (2021) stated that there is higher accumulation of metals in the sediment with increase in MP concentrations.

CONCLUSION

A large number of studies thus prove that microplastics have found entry in fresh water ecosystems through various sources. The behavior, prevalence and distribution of MP is affected by various factors like weather conditions, environmental stresses, industrial activities as well as urbanization around the rivers and lakes, etc. (Browne *et al*., 2011). The most common source of microplastic in the natural environment is the degradation of plastic products like fishing apparatuses, discarded plastic waste or through dry deposition. Microplastic in lakes and rivers act as potential polluting sources for the estuaries, deltas and oceans downstream and greatly determine the transportation, accumulation of microplastics in the estuarine and marine ecosystems (Pan *et al*., 2020). Climatic variability, estuarine gradient, shorelines with anthropogenic activities, situation in the watershed and low depth are important indicators in microplastic distribution (Alfonso *et al*., 2020) and show positive correlation with the MP abundance.

More elaborate studies are needed to evaluate the effects, residence time and fate of microplastics in the freshwater systems of the world. The degradation and fragmentation mechanism of microplastic in the freshwater systems requires extensive research. Due to the varied and scattered sources of MP in lakes and rivers there is a need to obtain samples that have wide temporal as well as spatial extent.

There are so far no standard sampling and monitoring methods to study the microplastic abundance. Most studies used manta trawl or plankton nets to sample microplastic particles from the surface layer of water bodies. There is still a restriction in the collection and sampling of nano sized plastic particles found in the natural environment. Standard and uniform methods of sampling, classification (based on size, shape, morphology), sample processing, identification and analysis of MP and uniform units of measurement need to be established.

The polymer type of the microplastic gives an indication of its source (Yan *et al*., 2019). But polymer identification and characterization protocol are still not unified. Visual identification on the basis of color and shape with the help of microscopy may not give reliable results in some cases. Sometimes many non-plastic particles are found in the samples but those may have some components of plastics or their additives hence proper component analysis is must to perform accurate identification and qualitative analysis. There is high degree of variability in the data available because of inconsistency in characteristics of microplastic found in the natural environment and in laboratory. Thus, it is necessary to improve our knowledge on nano- and microplastic abundance, distribution, degradation and fragmentation in freshwater systems of the world to develop promising strategies to reduce its entry and impact on human and animal health as well as on environment. Not many studies are there that have focused on the seasonal variation in microplastic abundance or variation in MP concentration over time. MP act as vectors carrying various harmful chemicals and metals as additives or by absorption on their surface thus increasing the toxic impact on living organisms. Aquatic animals and plants that are consumed as food in several parts of the world once infected with MP contaminate food chain.

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